Notes

Magnetic Torquing Scheme

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THIS note presents a simple scheme to use the earth's magnetic field as an angular momentum reversal device in the attitude control of satellites.[1] The basic control concept involved is the use of momentum storage devices supplemented on a discontinuous basis by magnetic torques for desaturation purposes. Reaction wheels are used to attitude control the vehicle by storing angular momentum, and the magnetic torques are used to remove angular momentum from the system. The system presented here performs only logical (not arithmetic) computations based upon angular momentum and magnetic field measurements and, therefore, is a simplification over the control techniques discussed in Refs. 2 and 3. This magnetic momentum removal system requires only a simple threshold measurement of both the reaction wheel speeds and the body axis components of the earth's magnetic field. These signals are combined using some simple logical operations to produce constant control moments. The concept discussed below is for three-axis attitude stabilization as opposed to those which control a spin stabilized vehicle.

A block diagram of the attitude control system under consideration is shown in Fig. 1. The block diagram shows the primary control loop, consisting of attitude sensors, compensation, and reaction wheels to control the body rotational dynamics, and the magnetic torquing system, consisting of magnetometers, logic, and magnetic moment generators. Because of disturbance torques acting on the orbiting satellite, the reaction wheel angular momentum storage will be fluctuating periodically with a component of secular angular momentum buildup. The function of the magnetic system is to remove this secular component of angular momentum.

A magnetic dipole moment in a magnetic field experiences a torque given by the cross product of the magnetic moment and the magnetic field vector. Written out in body coordinates, this relationship becomes

$$\begin{aligned} T_x &= M_y B_z - M_z B_y \\ T_y &= M_z B_x - M_x B_z \\ T_z &= M_x B_y - M_y B_x \end{aligned} \tag{1}$$

where the T's, M's, and B's are the body components of torque in Newton-meters, magnetic moment in amp-meter^2, magnetic field in weber/meter^2. It is immediately obvious from these equations that one can obtain a torque along any

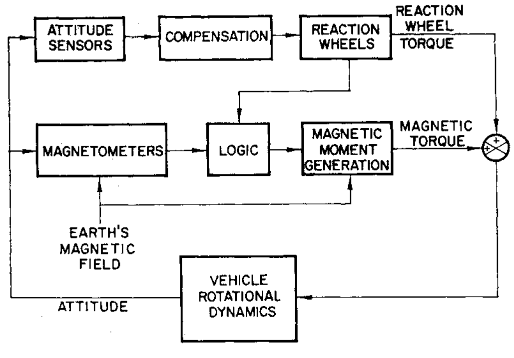

Fig. 1 System block diagram.

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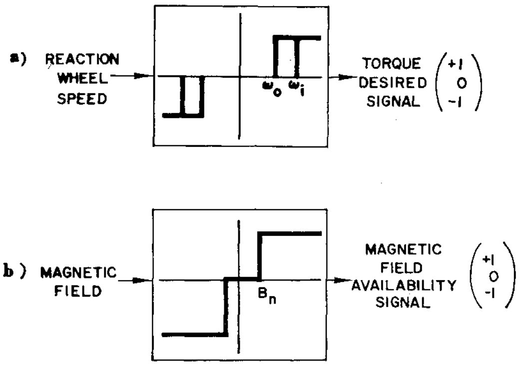

Fig. 2 a) Torque-desired logic; b) magnetic field availability logic.

given axis without causing a torque in another axis only if the magnetic field component along that axis is zero and magnetic moments are created only along the two perpendicular axes. It is also apparent from Eqs. (1) that the sign of the magnetic moment necessary to obtain a given direction of torque can be determined easily from the sign of the magnetic field present and the sign of the desired torque.

The mechanization of the foregoing remarks concerning Eqs. (1) leads to the logic referred to in Fig. 1. The torque-desired signal is generated for each axis as a function of reaction wheel speed ω as follows:

$$T_d = \begin{cases} -\mathrm{sgn}(\omega) & \omega > \omega_i \\ -1 & \omega_0 \leqslant \omega \leqslant \omega_i,\ T_d < 0 \\ +1 & -\omega_0 \geqslant \omega \geqslant -\omega_1,\ T_d > 0 \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

where ω_0 and ω_i are the wheel switch speeds that define the hysteresis band. This is shown in Fig. 2a, which represents the torque-desired logic for one axis. Note that T_d contains the necessary information concerning the sign of the desired torque. A magnetic field available signal is generated in each the axis from the magnetic fields present as follows:

$$B_a = \begin{cases} 0 & |B| < B_n \\ \mathrm{sgn} B & |B| \geq B_n \end{cases} \tag{3}$$

where B_n is the magnetic field threshold as defined in Fig. 2b.

Equation (3) defines the magnetometer requirements of the system and leads to characteristics as shown in Fig. 2b for each axis. Again the required sign information is contained in the magnetic field available signal.

The control signal for the magnetic moment generator in a given axis M_c can be formed directly from the torque desired signal and the magnetic field available signal in that axis by

$$M_c = \bar{B}_b T_d \tag{4}$$

where $\bar{B}_b = 0$ if $B_a = \pm 1$, and $\bar{B}_b = 1$ if $B_a = 0$. The sign of the magnetic moment to be generated can be determined from the sign of the magnetic field available signal and the torque desired signal as follows:

$$\begin{aligned} \mathrm{sgn}(M_{cx}) &= B_{by} T_{dz} - B_{bz} T_{dy} \\ \mathrm{sgn}(M_{cy}) &= B_{bz} T_{dx} - B_{bx} T_{dz} \\ \mathrm{sgn}(M_{cz}) &= B_{bx} T_{dy} - B_{by} T_{dx} \end{aligned} \tag{5}$$

All of the logical computations required thus can be made by simple combination of discrete signals. Figure 3 shows the complete logic for the z axis, including the magnetometer characteristics, for use of a y magnetic moment. The logic for the other axes is similar.

The magnetic desaturation on-time is determined by $(\omega_i - \omega_0)$, as can be seen from Fig. 2 and Eq. (2). A calibrated amount of angular momentum will be removed from a given axis upon engaging the magnetic moment, provided the magnetic field orientation remains favorable. This fact allows the system to use a fixed value of magnetic moment and vary

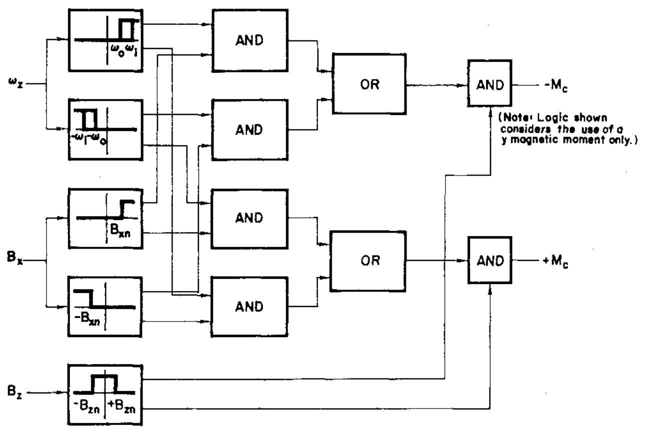

Fig. 3 Logic for z channel.

the magnetic torquing time. In addition, it permits the system operation to be independent of the magnitude of the magnetic field over the design range.†

The basic magnetic control concept discussed here has two major limitations. The scheme can be employed only if some type of angular momentum storage device is used for control, since the amount of angular momentum stored is used as basic information to operate the magnetic system. The other limitation concerns the magnetic field availability conditions. The magnetic field vector in body coordinates must (over a few orbits) exhibit sufficient motion to permit torques to be obtained in at least two of the body axes.‡ Thus, orbits for which the satellite spends a great deal of time in the vicinity of the geomagnetic equator will present more difficult design problems because of the lack of the motion of the magnetic field vector in body coordinates. Reference 1 contains a more detailed discussion of this problem.

The other limitations on the use of this scheme are those common to any type of control which uses the earth's magnetic field. The feasibility of this system for various orbital altitudes can be ascertained rather easily by examining the magnitude of the magnetic moment required to provide a given torque. If one considers the fraction of the orbit available for a given momentum correction to be fixed by the vehicle-magnetic field geometry, then torquing time available increases as the radius of the orbit to the $\frac{3}{2}$ power. The magnitude of the magnetic field available decreases as the cube of the radius. Hence the magnetic moment necessary to generate a given torque increases linearly with the period of the orbit. At very low altitudes, the aerodynamic torques cause the limitations on magnetic systems. As the altitudes are increased, the gravity gradient torques decrease, but the solar radiation torques remain essentially constant while the magnitude of the magnetic field decreases rapidly. This represents an upper altitude limit to the applicability of magnetic systems.

The particular system discussed here then can be used at any altitude where the magnetic torques can remove sufficient angular momentum from the vehicle to overcome the angular momentum buildup due to the secular components of the disturbance torques. It is possible, using currently available hardware, to generate sufficient magnetic torques even at altitudes corresponding to 30-hr circular orbits. For a 24-hr equatorial satellite, the magnetic field at the vehicle is a fixed vector; hence there will be a direction along which torque can never be obtained.§ Thus, in this case, the system must have an additional secular angular momentum removal device such as a gas jet.

The system presented in the foregoing uses the earth's magnetic field in a simple manner to desaturate the angular momentum storage devices used to attitude control a satellite vehicle. The simple logic and measurement operations required for the magnetic system can be performed in a reliable manner with simple components. The control system involved is flexible enough to permit use in a variety of different orbits and is hence a useful type of attitude control system to be considered for various missions.

For most missions, this system can be simplified somewhat to use only one magnetic moment generating element and two magnetometers. Note that the overall attitude control system for a fully controlled vehicle is now exactly parallel to a gas-jet reaction wheel system. Both systems use the reaction wheels for primary attitude control. The pneumatic system fulfills the desaturation requirement in one system while the magnetic system serves this purpose in the other. Note that a weight, power, and reliability comparison of the two systems now consists essentially of comparing these quantities for the pneumatic valves, propellant supply, tubing, and switching circuits vs the magnetometers, the wheel speed measurement, logic, and the magnetic moment generating element. It is apparent that for short lifetime vehicles and the current state of hardware development the magnetic system is not competitive. The magnetic system will begin to be competitive only for missions that require sufficiently long lifetimes such that the gas leakage or wear out of physically moving parts in the pneumatic system are important factors.

† This allows the system to be used for noncircular orbits within the altitude limitations noted.

‡ Only two are required, since for fully controlled vehicles the local vertical and velocity vector direction interchange in inertial space every 90° in orbit.

§ This situation is slightly modified due to yaw control for a vehicle with an oriented solar array, but the conclusions are similar.

References

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Stress-Strain Relations with Measured Cyclic Damping

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Introduction

EXPERIMENTAL results for material damping for structural metals generally are available (currently) only in the form of energy loss per cycle per unit volume of material vs steady-state, stress amplitude. This type of data reduction has been successful particularly in experimental studies, but its suppression of the stress-strain relations (by, in effect, integrating over a cycle) precludes its

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